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On quick reading of the attached paper I would guess that the author is a mathematician with considerable ^{and facile} depth. (Not a biologist or medical man by primary interest) His substantive area is one in which the Soviets are ^{particularly} strong but a US graduate student in mathematics or information theory could have done this work. The translation is unusually good or the author is very familiar with English. The work as presented is more of theoretical than practical interest. Perhaps "sanitization" means not disclosing the specific problem attacked. What was it.

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SYSTEMS ENGINEERING ANALYSIS OF DECISION MAKING RELIABILITY

Leningrad SISTEMOTEKHNICHESKOYE ISSLEDOVANIYE NADEZHNOSTI PRINYATIYA RESHENIY
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[Author's abstract of a dissertation in pursuit of the candidate of technical sciences degree by A. M. Shtern, specialty 05.252--Computer Technology, RSFSR Ministry of Higher and Secondary Special Education, Northwestern Correspondence Polytechnical Institute]

[Text] The reliability of decision making is acquiring special significance in modern production and in transportation and special systems. This problem has not only a certain amount of scientific significance but also considerable economic significance, since unreliable, ineffective decisions could lead to significant material losses and irreversible damage to the system.

Decision making is the most complex and least studied operation in the overall process of information processing. Decision making reliability is a function of many factors, and analysis of their influence upon decision making reliability is the topic of many researchers.

Because these problems are rather new, most research in this area has been basically devoted to particular problems associated with a particular technical system or particular characteristics of the operator. The task of developing and revealing decision making reliability criteria which would be universal, independent of the concrete type of information processing system, arises quite naturally. The effectiveness of the criteria revealed is dependent on the degree to which they permit control and prediction of the reliability of a systems engineering complex.

The present work, which analyzes decision making reliability from a systems engineering standpoint, deals with a number of tasks having the objective of producing practical recommendations on particular problems in reliable organization and planning of man-machine systems.

Basic Concepts

The decision making process can be described by a trajectory in a configurational search space. The search space is given by the set of states $\{N\}$

and the relationships existing among them. The decision structure can vary significantly depending on the nature of the relationships associating different points in the search space.

This work shows that in the case where the search space is a successive linear system, decision making is determined, and it assumes one of the following forms--maze, formal, convergence, closed, and interpolational.

When the probability element is introduced to the structure of relationships among states in the search space, decision making acquires a probabilistic structure and assumes the following forms--search, heuristic, divergence, open, and extrapolational.

These types of decision making can either be used separately, or they can be formed into complex combinations and sequences. In this case the determined and probabilistic types of decision making are always the polar types, and they are described by various mathematical tools. In the first case we use logical functions and determined networks, while in the second case we use statistical probability models and the theory of random processes. The determined approach presupposes that in all situations the system implements a certain given logical function, and all of its decisions are error-free. In the probabilistic approach we reject presence of an entirely error-free decision beforehand, substituting it by the probabilities of reaching acceptable decisions.

Special difficulties arise in formalizing the problem when the decision making process simultaneously possesses the qualities of both determined and probabilistic processes. In this case the search space may be determined in relation to a universal assessment and statistical in relation to a local one. This situation is the one most often encountered; however, formal methods for assessing the reliability of combined types of decision making are poorly developed. This is why we are forced to limit ourselves to examining just the polar type in practical situations. This dissertation demonstrates that use of a quasiclassical approach opens up a number of new possibilities for analyzing determined-probabilistic types of decision making. In this approach, the reliability of decisions can be assessed by the appropriate quasiclassical probability distributions.

It becomes much simpler to assess the reliability of decision making if we introduce the distance measure into the search space under analysis. This measure need not be defined as geometric length; in some measurable way it must relate points in the configurational space together. The units of distance measurement in the models examined here could be steps, bits, and so on. This work does not assess distances in concrete units; instead, relative distances are examined. This permits comparison of experimental results obtained in different informational environments.

The reliability of decision making depends on, in addition to the structure of the search space, the internal information characteristics of the system making decisions. The number of these information characteristics is

sufficiently large, and in the general case it is not as yet possible to find their optimum values. For the moment we are forced to limit ourselves to examining one or a few characteristics and revealing how the changes they experience influence the system's reliability. Two important factors defining the reliability of decision making are analyzed in this work:

- 1) The memory's information capacity Q ,
- 2) the level of prediction processes P .

The Basic Problem

Let the configurational search space be given with the appropriate metrics. The decision making process consists of a transition from some initial state to some final state (a goal). Let the generalized distance between the initial state and the goal be $|R|$.

We need to determine the range of variables Q and P producing a maximum in the reliability functions

$$\begin{aligned} \max F &= \max F(|R|, Q) \\ \max F &= \max F(|R|, P) \end{aligned}$$

where F is a function of the reliability of decision making. The limits are:

$$\begin{aligned} F_a &\in [0, 1] & F_p &\in (0, 1] \\ Q &\leq 2|R| & P &\leq |R| \end{aligned}$$

This problem was solved by means of phenomenological experiments and digital modeling of the decision making process with a BESM-6 digital computer. In parallel, the need arose for solving a number of background problems, the content of which will be presented below.

The Phenomenological Solution

The phenomenological analysis had an applied nature. Its tasks included determining a quantitative criterion of decision making reliability and developing the appropriate procedure permitting prediction of decision making reliability.

The configurational search space consisted of associated environments of varying complexity in this case. The decision process involved transformation of a certain initial situation into some final situation according to particular rules:

$$\begin{array}{c} x_1, x_2, x_3, x_4, x_5, x_6 \\ \downarrow \\ x_1, x_2, x_3, x_4, x_5, x_6 \end{array}$$

This transformation could be made with the assistance of a fixed number of substitutions, for example:

$$\begin{aligned} X_2 X_3 X_5 &\rightarrow X_8 X_4 X_{10} \\ X_7 X_1 X_5 &\rightarrow X_2 X_9 X_5 \end{aligned}$$

Inasmuch as the possibility for making a direct transition from the initial to the final situation was absent, the problem was solved in stages, in a prescribed number of steps.

The decision process was assumed to be reliable when the final situation was reached with a minimum number of steps and in minimum time, and it was assumed to be unreliable in the opposite case.

The distance $|R|$ between the initial and final situations was measured in units of information capacity in the short-term memory Q , with $|R|$ being given in the interval

$$0 < |R| < Q.$$

Tests revealed that decision making reliability is dependent in a certain way on the ratio between the memory's information capacity and the generalized distance $|R|$. When Q and R satisfy the inequality $Q/(|R|) > 1$, the decision making process is characterized by high reliability.

At the point $Q/(|R|)=1$ the reliability function experiences a first-order discontinuity, and the probability of error begins to grow monotonously as the ratio $Q/(|R|)$ decreases.

The Model Solution

The model solution of the problem formulated above was arrived at in digital form by running the problem in a digital computer. The search space was given as a quadratic matrix $\|A_{ij}\|$ with dimensionality n , and it was fed into the computer's memory. The values of elements a_{ij} were prescribed by a special procedure following a random law, in which case

$$1 \leq a_{ij} \leq 100.$$

The algorithm of the model's behavior entailed selection of a trajectory of movement from element a_{11} to element a_{nn} that was optimum in a particular way.

The probability of transition from element to element was prescribed as follows:

$$P_{a_{ij}, (i+1)j} + P_{a_{ij}, ai(j+1)} = 1.$$

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Considering this limitation on transitions, the distance $|R|$ between the initial state and the goal was $|R|=2(n-1)$ steps, where n is the dimensionality of the matrix.

Inasmuch as with the exception of dead-end points--that is, when $i=n$, $j \neq n$, $i \neq n$, $j=n$ --there was a possibility of binary choice at each point on the trajectory, the set of possible trajectories $\{T\}$ increased rapidly as the dimensionality of the matrix increased, in accordance with the law

$$T = \frac{(2n-2)!}{(n-1)!(n-1)!}$$

The values of the elements were summed as movement proceeded along the selected trajectory. A trajectory with a minimal final sum, S_{min} , was adopted as the optimum trajectory. The standard deviation from the minimum sum served as an indicator of decision making unreliability.

The internal information parameter P , characterizing the depth of prediction, was also introduced into the examination. Parameter P varied from 0 (random walk) to $|R|$ (absolute prediction). Thus each problem was solved $|R|+1$ times. The minimum sum of all possible P steps was chosen for each value P . As a result of such choice the trajectory led to a certain state a_{ij} , in which case if P is the depth of prediction and n is the choice number, then $i+j=nP+2$. Consequently the distance $|R|$ between two successive points was:

$$|R| = (i_{n+1} + j_{n+1}) - (i_n + j_n).$$

The result of the model solution consisted of the values:

$$D_{0,1} = (S_{min} - S_p)^2,$$

where D_0 corresponds to the case in which following several (or one) predictions the remaining number of steps is less than P but the subsequent trajectory is also predicted, and D_1 corresponds to the case in which the final element operates as a "mousetrap"--that is, whenever this element is attained the decision is irreversible.

Dispersions $D_{0,1}$ obtained by means of the modeling experiments were normalized with respect to the maximum and plotted as a function of the ratio between prediction depth P and distance $|R|$.

The most interesting point of the obtained dependence was its similarity with the results of the phenomenological trials, with the one difference that in this case the reliability function is continuous. The closeness of the phenomenological and modeling results indicates that the prediction level P depends on the possibility for placing the extrapolation vector in the short-term memory. If the memory's information capacity is too small for the required extrapolation vector, the decision making process becomes unreliable.

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Thus viewing reliability P of decision making as a function of $Q/(|R|)$ on one hand and as a function of $P/(|R|)$ on the other, we can say that both functions are partially equivalent, inasmuch as the information contained in them is practically identical:

$$P\left(\frac{Q}{|R|}\right) \sim P\left(\frac{P}{|R|}\right).$$

Given a fixed distance $|R|$ between the initial state and the goal, which must be traveled with a prediction depth not less than P if it is to be reliable, three types of situations are possible depending on the memory's information capacity Q :

- 1) Superreliable operation $P < Q$.
- 2) Reliable operation $P = Q$.
- 3) Unreliable operation $P > Q$.

The Background Problems

Functional Assessment of Decision Reliability

The distinct differences between determined reliable and probabilistic unreliable decisions revealed by solving the basic problem permitted the hypothesis that these types of decision making also differ in their functional organization.

To test this hypothesis we developed a procedure for assessing the balance of controllable and uncontrollable reactions. The main parameters used in this procedure were the EEG, the EMG, the GSR, the alpha-rhythm, and oscillations of EEG wave asymmetry $\Delta(t)$. Asymmetry oscillations $\Delta(t)$ were computed automatically with an MN-7 analog computer.

The experiments revealed typical differences in the changes experienced by the parameters analyzed in relation to different types of decision making.

Statistical analysis of reactions of parameter $\Delta(t)$ showed that the determined types of decision making cause a shift in the balance of controllable and uncontrollable reactions in the direction of controllable reactions. The reverse relationship exists in relation to probabilistic types of decisions.

A number of laws were revealed by analyzing changes in alpha-rhythm occurring during solution of determined and probabilistic problems. Thus the alpha-rhythm reaction permits us to divide the operators into four groups differing in reliability. Despite the fact that it does contain some information, indication of decision reliability on the basis of alpha-rhythm analysis is rather limited. This index must be used together with others if reliability

is to be checked and the balance of controllable and uncontrollable reactions is to be assessed effectively. The table below shows the typical properties of different groups of operators in relation to depression and activation of alpha-rhythm in the conditions of determined and probabilistic search.

Тип	Детерминированный поиск		Вероятностный поиск	
1	депрессия	95%	депрессия	98%
	активация	5%	активация	2%
2	депрессия	25%	депрессия	85%
	активация	75%	активация	15%
3	депрессия	74%	депрессия	30%
	активация	26%	активация	70%
4	депрессия	11%	депрессия	7%
	активация	89%	активация	93%

Key:

- | | |
|-------------------------|---------------|
| 1. Type | 4. Depression |
| 2. Determined search | 5. Activation |
| 3. Probabilistic search | |

Joint examination of electromyographic and galvanic skin responses produces a special advantage in assessing decision making reliability. These indices permit us to obtain quantitative relationships between decision making speed and reliability in standard situations and in stressful emergency situations. If we characterize the decision making process in standard conditions by Pt , where P is decision reliability and t is decision making time, then when a transition is made to a stressful emergency situation the averaged assessment is:

$$Pt/6.$$

The Reliability of Isoentropic and Entropic Decisions

The model solution of the basic problems showed that decision making reliability is dependent in a certain way on prediction level. In cases where the prediction vector cannot be placed in the memory's configurational space, it would be suitable to subject it to isoentropic transformation. This work showed that the methods of graph theory can be used for this purpose. If the search space and the prediction vector are given as the appropriate graphs, after normalizing them we can formulate the algorithm of isoentropic simplification of the initial graph.

In this case we examined the graph of the problem $G(X, \Gamma)$, given for the problem's set of elements $\{X\}$, and the graph of the information model $G(Y, T)$ formed in the decision making process. Here, $\{Y\}$ is the information model's set of elements and T is transformation of $\{Y\}$ into $\{Y\}$ [sic].

The information contained in the graph $G(Y, T)$ is equal to the information contained in the graph $G(X, \Gamma)$, with a precision up to the prediction error. These errors can differ depending on the extent to which $\{X\}$ exceeds the memory's information capacity $\{Q\}$. When $\{Q\} < \{X\}$, plotting of the final graph would proceed with certain errors until, by means of equivalent transformations of graph $G(X, \Gamma)$, a transformation is completed to graph $G(Q, T)$, where $\{Q\}$ is the set of elements of the memory's configurational space.

In view of the limited nature of $\{Q\}$, in addition to objective complexity the problem may be characterized by subjective complexity. The subjective probability P_c of attaining the goal may not coincide with the objective probability P_0 , depending on the tip of the problem graph from which the search for the decision begins. In these cases it would be more effective to subject the search space to entropic transformation. When this type of transformation is employed, the information contained in the graph does not remain constant.

A generalized measure of uncertainty, H , was obtained in the dissertation for cases in which the search space is subjected to entropic transformation:

$$H = \frac{\prod P_{ci}^{P_{ci}}}{\prod P_{oi}^{2P_{oi}}}$$

where P_{oi} is the objective probability of reaching the goal and P_{ci} is the subjective probability of reaching the goal.

In contrast to other measures of this type, the advantage of the obtained measure lies in the fact that when the subjective factor is eliminated, this measure transforms into conventional Wiener-Shannon entropy:

$$\lg \frac{\prod P_{ci}^{P_{ci}}}{\prod P_{oi}^{2P_{oi}}} \xrightarrow{P_c = P_0} - \sum P_{oi} \lg P_{oi}$$

Conclusion

Analysis of decision making processes from the standpoint of systems engineering makes it possible to refine the boundaries of reliable operation of man-machine systems.

The revealed laws governing decision making processes indicate the way information processes should be organized in a man-machine system so that the system would satisfy the required level of reliability.

The procedures developed here afford a possibility for control and prediction of the reliability of a systems engineering complex within certain limits.

The research produced the following basic results:

1. Different types of decision making were classified. Determined, probabilistic, and combined types of decision making were analyzed. It was demonstrated that these types differ in different situations in relation to the reliability criterion. Thus determined decisions are characterized by complete reproducibility. As a rule, probabilistic decisions are not reproducible. Partial reproducibility is a unique feature of combined types.

The methods for formalizing determined and probabilistic types of decision making are examined. Quantum-mechanics probabilities are suggested for assessment of the reliability of combined determined-probabilistic types.

2. It is established that the reliability of decision making is dependent on the relationship between the information capacities of the short-term memory and the environment of the problem. When the memory's information capacity exceeds the quantity of information processed, the decision making process is characterized by high reliability. If, however, the volume of information processed is greater than the memory's information capacity, the reliability function experiences a first-order discontinuity, and the probability of error grows monotonously as the information capacity of the environment of the problem increases.

A procedure for assessing decision making reliability accounting for both the characteristics of the information environment and the characteristics of the operator is developed on the basis of the revealed law. Use of this procedure in the planning of man-machine systems insures at least quasi-optimum organization of the system.

3. A digital model of the decision making process accounting for the prediction factor is developed. It is demonstrated that the reliability of decision making depends significantly on prediction depth. The reliability function grows monotonously with increase in the prediction vector, attaining a maximum when the prediction level becomes comparable with the generalized distance between the initial state and the goal. Inasmuch as prediction depth depends on the possibilities for placing the prediction vector within the short-term memory, transition from superreliable to unreliable operation occurs to the extent that the memory's configurational state is inadequate to hold the assigned prediction vector.

4. A method is proposed for assessing the balance of the operator's controllable and uncontrollable reactions, relying upon the use of electrophysiological

procedures. This method can be used both for occupational selection and for control of the reliability level during operation.

It is demonstrated that the reaction balance shifts in the direction of uncontrollable reactions in probabilistically organized environments. In determined environments, meanwhile, optimization of decision making is insured predominantly by controllable reactions. In this connection, if we are to heighten the reliability of a systems engineering complex we must make use of operators characterized by a maximum proportion of controllable reactions.

5. Objective criteria for detecting emergency states are revealed. These criteria permit determination of the relationship between decision making reliability and speed in ordinary conditions and in emergency conditions. In emergency conditions, stress functions significantly increase decision making speed but decrease reliability.

A method of controllable decision reproduction making it possible to surmount dead-end states in emergency situations is proposed on the basis of an analysis of stressful decision making. This method is ineffective when the lack of time is sizable.

6. The mechanisms of isoentropic and entropic information transformation are examined. The language of graph theory is used to formalize isoentropic processes. An algorithm of equivalent simplification of the environment of the problem, given in the form of a normalized graph, is proposed in application to isoentropic decision making processes.

A generalized information measure is introduced for cases of entropic information transformation. The proposed measure accounts for both the objective characteristics of signals depending on the technical components of the systems engineering complex, and the subjective characteristics dependent upon the operator's properties. The advantage of this measure lies in the fact that when the subjective factor is eliminated, it transforms into the conventional Wiener-Shannon measure of entropy.

7. Practical application of the procedures developed as a result of solving the basic problem demonstrated their economic effectiveness in relation to automated control systems.

The principal research results are presented in the following works:

1. "Effectiveness of Decision Making Processes," in "Nadezhnost' i effektivnost' kompleksnykh sistem 'chekovek-tehnika'" (Reliability and Effectiveness of Integrated Man-Machine Systems), Leningrad, 1971.
2. "Prediction of Operator Errors," in "Ispol'zovaniye EVM v geofizike" (Use of Computers in Geophysics), VIEMS, Moscow, 1971.

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3. "The Brain as a Measuring System," in "Biologicheskaya i meditsinskaya kibernetika i bionika" (Biological and Medical Cybernetics and Bionics), Issue 3, Kiev, 1970.
4. "A Stochastic Model of Brain Function," in "Materialy 4 Vsesoyuznoy konferentsii po neyrokibernetike" (Proceedings of the Fourth All-Union Conference on Neurocybernetics), Rostov-on-Don, 1970.
5. "The Problem of Determined and Probabilistic Thinking," in "Materialy 4 Vsesoyuznogo simposiума po kibernetike" (Proceedings of the Fourth All-Union Symposium on Cybernetics), Tbilisi, 1968.
6. "Information Quality as a Measure of Activity," in "Materialy konferentsii molodykh uchenykh" (Proceedings of the Young Scientists Conference), Izd-vo MGU, Moscow, 1968.
7. "Informational Interpretation of the Measurement Process," in "Materialy 4 nauchnoy konferentsii NGU" (Proceedings of the Fourth Scientific Conference of Novosibirsk State University), Novosibirsk, 1968.

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